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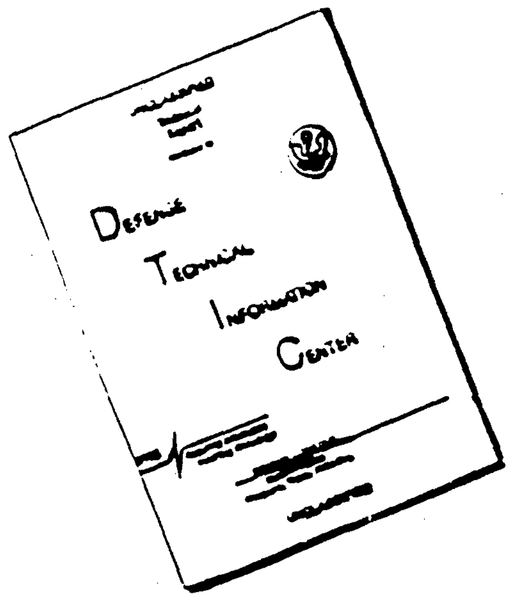

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Air force surveys in geophysics

No. 123

A diffusion-deposition model for in-flight release of fission fragments

M. L. Barad
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GRD

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A DIFFUSION-DEPOSITION MODEL FOR IN-FLIGHT RELEASE OF FISSION FRAGMENTS

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Task 86442

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ABSTRACT

A diffusion-deposition model is developed for use in estimating dosage levels due to in-flight release of fission fragments from a nuclear-powered aircraft. The model is based on the work of Sutton for diffusion and the work of Chamberlain for deposition. The model considers an elevated instantaneous point source and an elevated instantaneous line source oriented at an arbitrary angle to the mean wind direction.

Suggested values of the various deposition, rain-out, and diffusion parameters to be used with the model are presented along with a qualitative discussion of the uncertainties of the model and the suggested parameters.

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A DIFFUSION-DEPOSITION MODEL FOR IN-FLIGHT RELEASE OF FISSION FRAGMENTS

1. INTRODUCTION

The purposes of this study have been (1) to develop a diffusion-deposition model which, when combined with allowable fission-product dosages, will permit estimation of the allowable fission-product release rates during flight operations of nuclear aircraft, and (2) to suggest values of the parameters to be used in the model for a variety of meteorological conditions, flight altitudes, and flight patterns.

As a first approximation and with no significant loss of generality, the source of contamination has been treated either as a line source of finite length or as a point source at each of several fixed heights above sea level. Values of the parameters have been selected for flight altitudes of nuclear aircraft ranging from 500 to 35,000 feet above sea level. Flights in the stratosphere have not been considered.

It has been assumed that the fission products will be released as gases or as fine particulates. The particles are expected to exhibit a log normal distribution with a geometric mean diameter of 0.03μ and a geometric standard deviation of two. Also assumed is a constant release rate of each fission product during periods of operation on nuclear fuel.

Consideration has been given to the problem of exposure not only of the fixed receptor at ground level but of the moving receptor at aircraft flight levels.

2. THE DIFFUSION MODEL

2.1 Definition of Problem; Modeling Approximations

The diffusion model is derived to apply to the following specific problems associated with the normal operating release of radioactive materials by a nuclear-powered aircraft:

a. A source geometry of either a finite straight line or a circle laid out at some given height between 500 and 35,000 ft above the ground surface

(Authors' manuscript approved 13 April 1960.)

b. An orientation of the line source at an arbitrary angle to the mean wind direction at flight altitude

c. An estimate of the pollution levels to which a person on the ground may be exposed

d. An estimate of the pollution levels at an arbitrary height in the atmosphere to which a person flying in a private or commercial aircraft may be exposed

The finite time the aircraft will take to lay out the source has been ignored in development of the diffusion models. That is, it has been assumed that the source may be considered instantaneous in comparison with the diffusion times that characterize the problem (several hours to days). This reasoning also leads to the assumption that the source laid out in a circle may be treated as an instantaneous point source for exposure distances sufficiently far from the circle. The error introduced by these approximations is effectively nil for estimating contamination levels at the ground and at aircraft flight levels.

The most serious assumption made in the models is that the mean wind is constant in direction and speed throughout the portion of the atmosphere under consideration. In general this is an unrealistic assumption for application to "typical" atmospheric conditions. Nevertheless it is felt that the uncertainties arising in the selection of values for the various modeling parameters are large enough that trying to account rigorously for a nonuniform mean wind field introduces an unnecessary refinement. A qualitative discussion of the error this assumption introduces is given in Section 3 of this report.

The basic diffusion model chosen as a starting point for this problem is Sutton's model[12] for concentrations due to an instantaneous point source. The final model developed for the ground contamination problem enables one to make rough estimates of the following quantities for either the point source or the line source:

a. The exposure or time-integrated-concentration with or without deposition on the ground or scavenging by precipitation processes

b. The total deposition of material at a point on the ground due to natural pickup of the material by vegetation, objects, etc.

c. The total deposition of material at a point on the ground due to scavenging by precipitation processes

The model for estimating exposures at flight altitudes ignores the effect of deposition or scavenging on the air concentrations. Only two special cases of this problem are treated: an airplane flying through the cloud (1) parallel to the flight line of the nuclear-powered aircraft at the same speed, and (2) parallel to the mean wind direction.

Finally, in both models it is assumed that there is no difference between the power indices on distance for diffusion in the crosswind and vertical directions; that is, it is assumed that any anisotropy existing in the atmosphere on the scale of this problem can be accounted for by simply assigning different values to the so-called diffusion coefficients, C_y and C_z.

2.2 Model for Estimating Contamination at Ground Level

The equation for the concentration, χ, at a point on the ground, (x, y, o), due to an instantaneous point source located at $x = \ell \cos \theta$, $y = \ell \sin \theta$, $z = h$ (see Fig. 1) is given by

$$\chi(x,y,o,t) = \frac{2Q^*}{\pi^{3/2} C_x C_y C_z (\bar{u}t)^{3/2(2-n)}}$$

$$\exp\left\{-\frac{1}{(\bar{u}t)^{2-n}}\left[\frac{(x-\ell\cos\theta-\bar{u}t)^2}{C_x^2}+\frac{(y-\ell\sin\theta)^2}{C_y^2}+\frac{h^2}{C_z^2}\right]\right\} \quad (1)$$

where Q^* is the source strength (total amount of material); C_x, C_y and C_z are the diffusion coefficients with the dimensions of length to the $\frac{n}{2}$ power; n is the power index (dimensionless) mentioned previously; χ has the dimensions of quantity of material per unit volume;

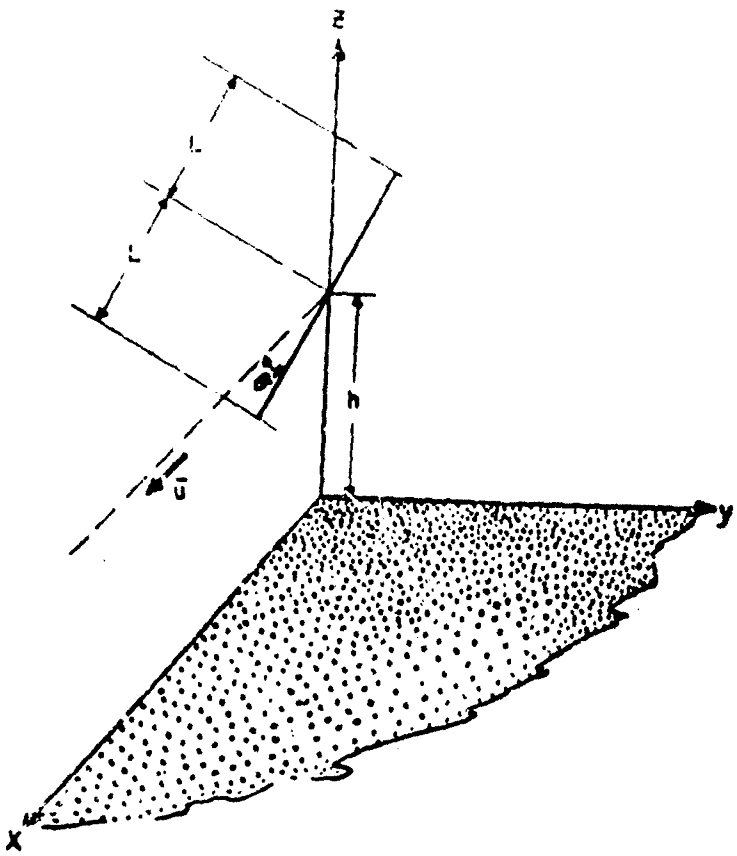

FIG. 1. Schematic diagram of geometry of source referred to a Cartesian coordinate system oriented with the x-axis parallel to the mean wind direction. Length of source = 2L; angle between line source and x-axis = θ; height of line source above ground plane (z = o) = h.

$\bar{u}$ is the mean wind speed; t is time after introduction of the source; and x, y, and z are the coordinates of a Cartesian system with the x-axis oriented parallel to the mean wind direction (Fig. 1). The origin of the coordinate system is the point defined by ℓ = o (x = y = o), z = o.

The total exposure, E_p , is obtained from Eq. (1) by integrating over time (zero to infinity) assuming that the spread of the cloud is small compared to the travel distances of the center of gravity of the cloud from its initial position. The result is

$$E_s(x, y, o) = \frac{2Q^*}{\pi C_y C_z \bar{u} (x - \ell \cos\theta)^{2-n}}$$

$$\exp\left\{ - \frac{1}{(x - \ell \cos\theta)^{2-n}} \left[\frac{(y - \ell \sin\theta)^2}{C_y^2} + \frac{h^2}{C_z^2} \right] \right\} \tag{2}$$

The analogous quantity, E, for an instantaneous line source is obtained by integrating Eq. (2) over ℓ from $-L$ to $+L$ for a line source of length $2L$:

$$E(x, y, o) = \frac{2Q}{\pi C_y C_z \bar{u}} \int_{-L}^{\lambda(x)} \frac{1}{(x - \ell \cos\theta)^{2-n}}$$

$$\exp\left\{ - \frac{1}{(x - \ell \cos\theta)^{2-n}} \left[\frac{(y - \ell \sin\theta)^2}{C_y^2} + \frac{h^2}{C_z^2} \right] \right\} d\ell \tag{3}$$

$$\text{where } \lambda(x) = \begin{cases} \dfrac{x}{\cos\theta} & \text{for } x < L\cos\theta \;;\; \theta \neq 90° \\ L & \text{for } x > L\cos\theta \\ L & \text{for } \theta = 90° : x > o \end{cases} \tag{4}$$

The source strength, Q, must now be given in terms of amount of material per unit length to make the equation dimensionally consistent.

If there were no deposition or precipitation scavenging, Eq. (3) would give estimates of the exposure near the ground upon selection of suitable values for the various parameters. It is felt, however, that these latter processes may be important, particularly for those releases relatively near the ground surface. An attempt to account for these effects is made following the work of Chamberlain.[5]

The total deposition, Δ, at a point on the ground is given by

$$\Delta(x, y, o) = V_g \; E(x, y, o) = -\frac{\partial Q}{\partial x} \tag{5}$$

where Δ has the dimensions of quantity of material per unit area; V_g is the deposition rate. The far right-hand side of Eq. (5) indicates the fact that deposition acts to deplete the effective source strength of the cloud. Substituting Eq. (3) into Eq. (5), solving for Q, and substituting the result back into Eq. (3) gives

$$E(x,y,o) = \frac{2Q_o}{\pi C_y C_z \bar{u}} \left\{ \exp - \int_{-L\cos\theta}^{x} \int_{-L}^{\delta(x)} \frac{2V_g}{\pi C_y C_z \bar{u} (x - \ell\cos\theta)^{2-n}} \right.$$

$$\left. \exp\left[-\frac{1}{(x-\ell\cos\theta)^{2-n}} \left(\frac{(y-\ell\sin\theta)^2}{C_y^2} + \frac{h^2}{C_z^2}\right)\right] d\ell \, dx \right\} \tag{6}$$

$$\left\{ \int_{-L}^{\delta(x)} \frac{1}{(x-\ell\cos\theta)^{2-n}} \exp\left[-\frac{1}{(x-\ell\cos\theta)^{2-n}} \left(\frac{(y-\ell\sin\theta)^2}{C_y^2} + \frac{h^2}{C_z^2}\right)\right] d\ell \right\}$$

where Q_o is the source strength at $x = o$ (or at the initial time). The deposition, Δ, is then given by multiplying Eq. (6) by V_g, the deposition rate.

The scavenging of the particulate or contaminant cloud by precipitation processes is treated here as a two-stage process. Because of the small particle sizes expected in the contaminate cloud, one must first estimate the fraction of exposure that becomes contained in the cloud droplets. The second step is to estimate the efficiency of precipitation (rain) in removing the cloud droplets. The actual precipitation depletes the effective source strength of the particulate cloud whereas the acquisition of particles by cloud droplets has no effect on the exposures. Once precipitation has started, the exposure at the ground (following Chamberlain[5]) is given by

$$E(x, y, 0) = \frac{2Q_0 \exp\left[-\Lambda(x - x_b)/\bar{u}\right]}{\pi C_y C_z \bar{u}} \int_{-L}^{\ell(x)} \frac{1}{(x - \ell \cos\theta)^{2-n}}$$

$$\exp\left\{- \frac{1}{(x - \ell \cos\theta)^{2-n}} \left[\frac{(y - \ell \sin\theta)^2}{C_y^2} + \frac{h^2}{C_z^2}\right]\right\} d\ell \qquad (7)$$

where Λ is the elimination constant (units of time^{-1}) that characterizes the depletion of cloud droplets by precipitation; x_b is the downwind distance where precipitation scavenging first begins; that is,

$$\Lambda = \begin{cases} 0 \; ; & x < x_b \\ \Lambda \; ; & x \geq x_b \end{cases} \qquad . \qquad (8)$$

The fraction of the exposure actually contained in cloud droplets is given by (see Greenfield[8]):

$$\left\{1 - \exp\left[-\dot{\gamma}(x - x_a)/\bar{u}\right]\right\} E(x, y, z)$$

where

$$\gamma = \begin{cases} 0 \; ; & x < x_a \\ \dot{\gamma} \; ; & x \geq x_a \end{cases} \qquad (9)$$

is the time constant describing the cloud droplet efficiency in acquiring particles, and x_a is the downwind distance where cloud droplets first appear. The total amount of material per unit area deposited on the ground is obtained by integrating $\Lambda \left\{1 - \exp\left[-\dot{\gamma}(x - x_a)/\bar{u}\right]\right\} E$ over height under the assumptions that the removal processes are uniform with height and that the water-droplet cloud completely embraces the particulate cloud. Dry deposition and reflection at the surface when precipitation occurs are both ignored. Thus

$$P(x, y, o) = \Lambda \left\{ 1 - \exp\left[-\gamma (x - x_a)/\bar{u}\right] \right\} \int_0^\infty E(x, y, z)\, dz$$

$$= \left\{ 1 - \exp\left[-\gamma (x - x_a)/\bar{u}\right] \right\} \frac{\Lambda Q_0 \exp\left[-(x - x_b)/\bar{u}\right]}{\pi^{1/2} C_y \bar{u}}$$

$$\int_{-L}^{\delta(x)} \frac{1}{(x - \ell \cos\theta)^{\frac{2-n}{2}}} \exp\left[- \frac{(y - \ell \sin\theta)^2}{C_y^2 (x - \ell \cos\theta)^{2-n}} \right] d\ell \tag{10}$$

If a point source of strength Q_0^* instead of a finite line source is considered, the above modeling equations are simplified by setting ℓ identically equal to zero which eliminates the integrations with respect to ℓ. Thus, to summarize, the solutions for the point source problem are as follows:

a. Exposure, with dry deposition,

$$E_p(x, y, o) = \frac{2 Q_0^*}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[- \frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right]$$

$$\exp\left[- \int_0^x \frac{2 V_g}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[- \frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right] dx \right] \tag{11}$$

b. Deposition

$$\Delta_p(x, y, o) = \frac{2 V_g Q_0^*}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[- \frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right]$$

$$\exp\left\{ - \int_0^x \frac{2 V_g}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[- \frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right] dx \right\} \tag{12}$$

c. Exposure, with precipitation scavenging,

$$E_p(x, y, o) = \frac{2Q_0' \exp\left[-\Lambda(x - x_b)/\bar{u}\right]}{\pi C_y C_z \bar{u}\, x^{2-n}}$$

$$\exp\left[-\frac{1}{x^{2-n}}\left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2}\right)\right] \tag{13}$$

d. Deposition due to precipitation scavenging,

$$P_p(x, y, o) = \left\{1 - \exp\left[-\psi(x - x_a)/\bar{u}\right]\right\} \frac{\Lambda Q_0' \exp\left[-\Lambda(x - x_b)/\bar{u}\right]}{\pi^{1/2} C_y \bar{u}\, x^{\frac{2-n}{2}}}$$

$$\exp\left[-\frac{y^2}{C_y^2\, x^{2-n}}\right] \tag{14}$$

2.3 Model for Estimating Contamination for Privately Flown Aircraft

Let us imagine a privately-owned or commercial plane flying a course parallel to the source line laid out by the nuclear-powered aircraft. To simplify the problem mathematically, it is assumed that the planes have equal flight speeds and that the end effects due to the finite length of the source can be neglected. The source can now be treated as a fixed continuous point source and the exposed plane as a fixed point relative to the source. Surface deposition does not enter this problem and precipitation scavenging is neglected. The concentration at the exposed plane is then given by

$$\chi(x, y, z) = \frac{Q'}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[-\frac{1}{x^{2-n}}\left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right] \tag{15}$$

where the Cartesian coordinate systems has its origin at the exhaust point of the nuclear-powered aircraft; Q' is the amount of material released per unit time.

The exposure for the private plane is given, within the limits of the preceding assumptions, by

$$E(x, y, z) = \frac{\bar{Q}}{\pi C_y C_z \bar{u}\, x^{2-n}} \exp\left[-\frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{z^2}{C_z^2} \right) \right] \tag{16}$$

where $\bar{Q}$ is the total amount of material released in flying a line of length 2L; that is

$$\bar{Q} = \int_0^{2L/V_a} Q' \, dt$$

where V_a is the airspeed of the airplane. This case is included because it serves to define a region in the vicinity of the nuclear-powered aircraft from which other air traffic must be restricted. It is the most serious conceivable air contamination problem arising from normal operation of the nuclear-powered aircraft.

The case of a privately-owned plane flying parallel to the mean wind direction is treated here for an infinite line source oriented perpendicular to the mean wind. This is not a particularly serious simplification if the exposed plane flies along the x-axis of the finite line source; in effect, the model neglects the end effects of the real finite-length line source.

The concentration at a point (x, z) relative to the initial release line is given by

$$\chi(x, z, t) = \frac{Q_0}{\pi C_y C_z (\bar{u}t)^{2-n}} \exp\left\{ -\frac{1}{(\bar{u}t)^{2-n}} \left[\frac{(x - \bar{u}t)^2}{C_x^2} + \frac{z^2}{C_z^2} \right] \right\} \tag{17}$$

An approximate solution to the contamination problem is obtained by assuming that the exposed plane passes through the cloud as described at some fixed time, t. The aircraft exposure is thus

$$E(z,t) = \int_0^\infty X \, d\tau = \int_0^\infty X\,(x,z,t)\,\frac{dx}{V_a} =$$

$$\frac{Q_0}{\pi^{1/2} C_z V_a (\bar{u}\,t)^{\frac{2-n}{2}}} \exp\left[-\frac{z^2}{C_z^2 (\bar{u}\,t)^{2-n}}\right] \tag{18}$$

where V_a is the airspeed of the exposed plane; or, for $X = \bar{u}t$, the position of the center of gravity of the cloud from its initial position,

$$E(X,z) = \frac{Q_0}{\pi^{1/2} C_z V_a X^{\frac{2-n}{2}}} \exp\left[-\frac{z^2}{C_z^2 X^{2-n}}\right] \; . \tag{19}$$

3. VALUES OF PARAMETERS

3.1 Ground-level Exposure, Point or Line Source

The determination of suitable values for $\bar{u}$, n, C_y, and C_z for this part of the problem is primarily governed by the fact that the release is at a relatively high level in the atmosphere whereas estimates of ground-level exposures are required. All four of these parameters vary with height with the greatest percentage variation probably being that of the wind speed, $\bar{u}$. The parameters also have horizontal and time variations, but these variations are considered secondary in importance to the vertical variations as far as estimating exposures at the ground are concerned.

In general the parameters have been given values that are averaged over the depth of the atmosphere from the surface to the release altitude, h. Several heights are chosen between 500 and 35,000 ft for this purpose.

Values of $\bar{u}$ were derived from tabulations presented by Crutcher[7]; these tabulations provide seasonal means of wind speed and direction as well as time variability vs. height for many weather-observing stations in the Northern Hemisphere. Three stations are chosen as examples to indicate roughly the degree of variability one might expect due to such factors as geographical location and season of the year. The wind data for these three stations, (Seoul, Korea; San Diego, California; and San Juan, Puerto Rico) are given in Table 1.

The directions of the mean winds are also important and should be determined for the region of interest in order to assess downwind effects.

For planning purposes, estimates of extremes of exposure expected at the ground due to flight-line orientation can be obtained by using values of $\theta = 90°$ (line source crosswind) and $\theta = 0°$ (line source parallel to mean wind) in the generalized model.

It must be emphasized that the actual wind observed at any time will generally be quite different from the mean values given in Table 1. For a given mean wind direction at a given level in the atmosphere, the observed wind speed can be expected to be between zero and the mean speed in that direction 25 percent of the time.

Additionally, it must be recognized that the existence of wind shear with height has a profound effect upon exposure estimates at ground level in that shear enhances the diffusing power of the atmosphere. This means that the model tends to overestimate the exposure in regions of appreciable shear.

Selection of suitable values of n, C_y, and C_z must take into account the variation of these parameters with thermal stability as well as with height. In general, n increases with increasing thermal stability. However, available observational data indicate no systematic variation of C_y and C_z with thermal stability.

Under the assumption that atmospheric anisotropy need not be accounted for by assigning values to an n_y and an n_z, results quoted

TABLE 1. Five-year seasonal mean wind speeds (m/sec) averaged over depths of the atmosphere between the height of receptor and the flight altitude of the nuclear-powered aircraft for Seoul, Korea; San Diego, California; and San Juan, Puerto Rico.

Seoul, Korea (37° 34'N; 126° 58'E)

HEIGHT (thsds of feet)	SEASON	HEIGHT (Thsds of feet) 0-0.5	5	10	15	20	25	30	35
0-0.5	Winter	8	8	10	13	15	18	22	25
	Spring	4	4	6	8	10	13	15	18
	Summer	2	2	3	4	5	6	7	9
	Fall	4	4	6	8	10	13	15	18
5	Winter		9	12	13	18	21	25	30
	Spring		4	7	9	12	14	16	19
	Summer		2	3	4	5	6	7	8
	Fall		4	7	9	12	14	18	19
10	Winter			15	18	21	24	27	30
	Spring			9	12	14	16	19	20
	Summer			4	5	6	7	8	9
	Fall			9	12	14	16	19	21
15	Winter				21	24	27	30	33
	Spring				14	17	19	22	24
	Summer				6	7	8	9	10
	Fall				14	17	19	22	33
20	Winter					27	30	33	35
	Spring					19	22	24	25
	Summer					8	9	10	11
	Fall					19	22	24	25
25	Winter						33	37	39
	Spring						24	26	28
	Summer						10	11	12
	Fall						24	26	28
30	Winter							40	41
	Spring							28	30
	Summer							12	13
	Fall							28	30
35	Winter								42
	Spring								31
	Summer								14
	Fall								32

TABLE 1 (Cont.)

San Diego, California (32° 44'N; 117° 10'W)

HEIGHT (thsds of feet)	SEASON	HEIGHT (Thsds of feet) 0-0.5	5	10	15	20	25	30	35
0-0.5	Winter	2	2	4	6	8	10	12	14
	Spring	3	3	4	5	7	9	11	12
	Summer	2	2	3	3	5	5	6	7
	Fall	2	2	3	3	5	6	7	8
5	Winter		2	4	6	8	11	12	14
	Spring		3	4	5	7	9	11	12
	Summer		2	3	4	5	5	7	8
	Fall		2	3	3	5	6	8	9
10	Winter			6	9	11	13	14	15
	Spring			5	7	8	11	12	13
	Summer			4	5	6	7	8	8
	Fall			3	4	6	7	8	9
15	Winter				11	13	15	17	19
	Spring				8	10	12	14	15
	Summer				5	6	7	8	9
	Fall				5	7	8	9	10
20	Winter					15	17	19	20
	Spring					11	14	15	16
	Summer					7	8	9	10
	Fall					8	10	11	12
25	Winter						19	21	22
	Spring						16	18	19
	Summer						9	10	11
	Fall						11	12	13
30	Winter							22	24
	Spring							19	20
	Summer							11	12
	Fall							13	14
35	Winter								25
	Spring								21
	Summer								13
	Fall								15

TABLE 1 (Cont.)

San Juan, Puerto Rico (18° 28'N; 66° 07'W)

HEIGHT (thsds of feet)	SEASON	HEIGHT (Thsds of feet) 0-0.5	5	10	15	20	25	30	35
0-0.5	Winter	7	7	6	5	6	9	11	14
	Spring	5	5	4	5	6	8	10	13
	Summer	8	8	7	7	4	5	5	6
	Fall	5	5	4	4	4	4	4	5
5	Winter		7	6	5	6	9	12	14
	Spring		5	4	5	6	8	10	13
	Summer		8	7	7	6	5	5	6
	Fall		5	5	4	4	4	4	5
10	Winter			4	4	5	7	10	12
	Spring			2	3	4	6	8	11
	Summer			6	6	5	4	4	5
	Fall			4	4	3	3	3	4
15	Winter				3	4	7	9	11
	Spring				4	5	7	9	12
	Summer				5	4	4	4	4
	Fall				3	3	3	3	4
20	Winter					5	8	10	12
	Spring					6	8	10	13
	Summer					3	3	3	3
	Fall					2	2	2	3
25	Winter						10	13	15
	Spring						10	12	15
	Summer						2	2	3
	Fall						2	2	3
30	Winter							15	17
	Spring							14	17
	Summer							2	3
	Fall							2	3
35	Winter								19
	Spring								19
	Summer								3
	Fall								4

in the USAEC WASH 740 report,[14] by Barad and Haugen,[2] and by Convair[6] are essentially consistent with Sutton's recommendations[13] for the variation of n with thermal stability. At levels in the atmosphere well above the gradient level, however, variations in thermal stability are relatively small and a value of n slightly greater than the neutral value is probably appropriate.

Computations of C_y from data published by Wilkins[15] for large-scale diffusion, assuming an n value of 0.25, led to values for C_y that show a slight tendency to decrease with height but that are consistent with values of C_y arising from several other sources; for example, references 2, 9, and 14.

To determine suitable values of C_z, three recently conducted experiments over a range of about 100 miles were analyzed with a rate of deposition of 2 cm/sec for the fluorescent pigment used and a value of n of 0.25. The release altitude for these experiments was about 2000 ft. Thermal stability ranged from slightly stable to slightly unstable. The resulting values of C_z are essentially consistent with Prairie Grass data[2] and Sutton's suggested empirical equation[13] for the variation of "C" with height, but they are an order of magnitude less than the values recommended in the USAEC WASH 740 report.[14] However, since the three experiments analyzed are directly pertinent to the problem of line sources, it is felt that the analysis of these data must guide the choice of values for C_z until further experimental evidence is available.

The values recommended for n, C_y, and C_z as a function of height and thermal stability are summarized in Table 2. Probable limits of these values are also tabulated for the purpose of assessing the degree of variability one might expect in these parameters. It is emphasized that this tabulation of values is for estimating exposure at the ground arising from release of material at a given altitude h; that is, the values represent rough averages over the heights involved.

For the small particle sizes considered in this study, the deposition of material from a cloud to the ground during non-precipitation

TABLE 2. Values of n, C_y, and C_z vs. height of release and thermal stability to use in models for estimating exposure at the ground. Ranges of the values are indicated in parentheses.

HEIGHT (ft)	STABILITY	C_y ($m^{n/2}$)	C_z ($m^{n/2}$)	n
	Lapse	0.40(0.2-0.6)	0.05(0.01-0.1)	0.15(0.0-0.20)
	Neutral	" "	" "	0.25(0.20-0.35)
500	Moderate Inversion	" "	" "	0.33(0.30-0.45)
	Strong Inversion	" "	" "	0.50(0.45-0.80)
	Lapse	" "	" "	0.20(0.0 -0.20)
	Neutral	" "	" "	0.25(0.20-0.35)
5,000	Moderate Inversion	" "	" "	0.33(0.30-0.45)
	Strong Inversion	" "	" "	0.50(0.45-0.80)
	Lapse	" "	" "	0.20(0.0 -0.20)
	Neutral	" "	" "	0.25(0.20-0.35)
10,000	Moderate Inversion	" "	" "	0.33(0.30-0.45)
	Strong Inversion	" "	" "	0.50(0.45-0.80)
15,000		0.30(0.2-0.5)	0.03(0.01-0.08)	0.30(0.20-0.35)
20,000		" "	" "	" "
25,000		" "	" "	" "
30,000		" "	" "	" "
35,000		" "	" "	" "

conditions is believed to be limited by the meteorological diffusion parameters and the processes of impaction and sticking to objects on the ground rather than the settling of particles through the influence of gravity. Particles brought through the boundary layer to the ground by the turbulent diffusion process deposit on vegetation or other ground objects by inertial impaction and diffusion and stick by electrostatic forces, chemical attraction, or other means. Investigations of this process during neutral atmospheric stability, assuming that the rate of transfer of material across the boundary layer is equivalent to the rate of transfer of momentum across the boundary layer, indicate that the velocity of deposition should vary directly with wind speed. There is also reason to believe that the deposition velocity should change with stability in the lower layers of the atmosphere, being greater during unstable conditions than during inversion conditions.

Data on the velocity of deposition of I^{131} at Hanford and from British experiments indicate a value of 2.7 cm/sec is appropriate. Calculations of the deposition velocity, assuming that the flux of matter is equal to the flux of momentum during neutral conditions, result in about the same value. Measurement of the velocity of deposition of fission products resulting from arc burning of uranium has indicated a lower deposition velocity of about 0.1 cm/sec. The difference between the I^{131} and the fission product aerosol values is believed to be due primarily to a net difference in impaction, retention, or adsorption efficiency on the surface.

For the model proposed, the velocity of deposition is assumed to vary directly with the wind speed near the ground (say 2 meters height) with an arbitrary but theoretically tractable allowance made for the change due to atmospheric stability. They are given as a ratio to the wind speed. Separate values are given for particulates and halogens based on the experience at Hanford and English experiments for the halogens and English experiments for the fine particulates. The noble gases do not appear to deposit appreciably.

In an analysis of rain-scavenging of radioactive particulate matter from the atmosphere, Greenfield[8] found that direct interaction of raindrops and particles does not account for the efficient removal of material whose diameter is below approximately one micron diameter. However, he was able to explain the removal of these smaller particles by allowing the particles to mix with the water cloud before the rain starts so that the small particles that are scavenged by coagulation are then placed in a position to be more efficiently removed by the rain.

Our present knowledge is still too inadequate for anything beyond a suggestion of the scavenging processes in the atmosphere for such finely divided material as envisaged from the reactor. Evidence from world-wide fallout studies suggest that the very small fission products become attached to the natural aerosol particles and then have a history in the atmosphere similar to that of the host. The time required for such a condition to near completion is not known, but one would not

TABLE 3. Deposition parameters for particulates and halogens vs. thermal stability. After Healy (9: p. 6)

THERMAL STABILITY	$V_g/\bar{u}_2$	
	Particulates*	Halogens
Strong Inversion	1.5×10^{-4}	2.4×10^{-3}
Moderate Inversion	2.2×10^{-4}	3.4×10^{-3}
Neutral	3×10^{-4}	4.6×10^{-3}
Unstable	6×10^{-4}	8×10^{-3}

* For fission products attached to natural aerosols a figure of about one-third that for halogens is suggested rather than the above figures for particulates. This figure arises from qualitative appraisal of world-wide fallout and cannot be defended quantitatively at this time.

expect it to be as rapid as the coagulation with larger water droplets because of the relative differences in mean free paths. Junge[11] suggests that the predominant cause of the modification in size-distribution of the stratospheric aerosols on the way down through the troposphere is the repeated cycle of condensation and evaporation of clouds, a process requiring considerable time.

For the present calculation we assumed that the predominant mechanism for removing these small particles from the air by rain must be cloud-droplet-scavenging coupled with later scavenging of the cloud droplets by larger raindrops. Effective scavenging constants, that is, the time required for the number of particles to decrease to 1/e of the initial value, for the contaminant activity in the presence of cloud droplets characteristic of stratus and cumulus cloud conditions were computed from Greenfield's curves assuming that the activity was proportional to the volume of the particle. The cloud characteristics used by Greenfield compared favorably with later data reported by aufm Kampe and Weickmann[1] and were not altered. The calculated times required for one-half the activity from the air to enter the cloud

TABLE 4. Parameters for cloud-droplet scavenging of particulate cloud and precipitation scavenging of cloud droplets.

Height of Release (ft)	Cloud Type	Rainfall Rate (mm/hr)	Scavenging Constant, γ (sec^{-1})	Elimination Constant, Λ (sec^{-1})
500 and 5000	Stratus	0.5	5×10^{-6}	2×10^{-4}
All heights 5,000-35,000	Cumulus	3.5	6×10^{-5}	1×10^{-3}

droplets, that is, the γ values called for in the model after mixing of the cloud and contaminant particles, are given in Table 4.

The amount of activity that will fall out as rain will depend upon the time of mixing of the contaminant and cloud elements and the rate at which the cloud droplets are swept from the cloud by larger raindrops. This latter aspect of the problem was studied by Chamberlain[5] using Langmuir's theory[10] of the formation of raindrops by coalescence with smaller raindrops and Best's relationship[4] between raindrop size and rainfall rate. Results of Chamberlain's study applicable to this problem are also summarized in Table 4.

The scavenging of fission products by cloud droplets can only occur at heights at which the clouds form. The heights of the various types of clouds vary within wide limits. However, scavenging by stratus clouds should be limited to 5000 ft and below, whereas scavenging by cumuliform clouds can occur at any height between 2000 ft and the tropopause.

3.2 Exposure to Private Aircraft, Line or Point Source

For this part of the problem, only the determination of values of $\bar{u}$ follows the same procedure as outlined in the preceding discussion. Seasonal mean values for the three stations chosen as examples of the types of wind distributions to expect are given in Table 1 (page 13).

The choice of values for C_y, C_z, and n, however, requires a

somewhat different procedure. The diffusion problem we are considering here is generally restricted to a layer of the atmosphere that is not particularly deep nor close to the surface. If the layer of concern is well above the gradient wind level in the atmosphere, that is, about 10,000 ft or more above the surface, one would expect the turbulence to be nearly isotropic. If the atmosphere were incompressible or the mean tropospheric lapse rate neutral rather than slightly stable, one could use theoretical arguments to conclude an isotropic field of turbulence in the free atmosphere. In any event it is difficult to conceive that the diffusion coefficients, C_y and C_z, can differ by roughly an order of magnitude so long as diffusion through the atmospheric friction layer is not involved. There are no data concerning vertical diffusion through layers of the free atmosphere that can be brought to bear on this problem, so the best one can do here is to estimate a reasonable value for C_z. In line with the discussion outlined above, one would expect C_z to be slightly less than C_y in the mean, although at times it could conceivably be equal to or greater than C_y.

Thus, if both planes* are flying at 10,000 ft or more above the surface, we recommend the following values for the parameters: C_y, 0.3; C_z, 0.1; n, 0.30. Variations of these parameters are probably within the ranges: $0.2 < C_y \leq 0.5$; $0.05 \leq C_z \leq 0.2$; $0.20 \leq n \leq 0.35$.

On the other hand, if the flight altitude of either plane is nearer 5000 than 10,000 ft or below 5000 ft, the values of C_y, C_z, and n given in Table 2 should be used.

4. DISCUSSION

Most of the remarks of this section are intended to provide perspective for use in evaluating the significance of exposure levels estimated from the foregoing models. In general the approach to the problem is conventional with methods directly obtained from the literature applied where possible. It is hoped that individuals using this document will realize the uncertainties and the lack of precision of

* A privately-owned or commercial and a nuclear-powered aircraft)

many of the calculational techniques used and will appreciate the role of the "educated guess," both in deriving the model parameters and in interpreting the results.

Even to this day there is no real standard set of numbers to use in the diffusion model and each "expert" will use his own. In fact none of the many attempts to derive expressions for the diffusion of gases and small particulate materials in the atmosphere can be rigorously defended on theoretical grounds, but most can be used with acceptable accuracy, if appropriate values of the diffusion parameters are introduced and the limitations of the models properly assessed. Consequently there is a common reluctance among atmospheric physicists to attach quantitative estimates to phenomena so vague and uncertain as deposition and rainout or cloud scavenging, particularly since assignment of numerical estimations conveys an erroneous impression of the confidence or firmness of the knowledge constituting the basis of the estimate.

The atmospheric diffusion model chosen utilizes the fact that the damage from radioactive materials is the result of the total integrated concentration or the product of the concentration and time and not of the concentration itself. Thus the results are expressed in integrated exposure regardless of the time of passage of the material. The exposure limits to be applied in calculating the permissible release rates can then be expressed in terms of the integrated concentration at the site of interest, with the amount of any isotope in existence at this time being corrected for the decay time since release.

Care must be used in summing the components of the exposure at various points in the environs for determining permissible release rates. The external exposure to humans at ground level will arise from material remaining in the cloud and that deposited on the ground so that the change in size of the cloud and deposition pattern with distance must be taken into account. Further, isotopic fractionation of both the material in the cloud and that deposited may occur at downwind points due to different deposition velocities of the isotopes. All of these

factors must be properly accounted for in using the model.

The diffusion model is only expected to provide an average behavior of the contaminants. For essentially instantaneous releases, a large variety of behaviors is possible. Discrete puffs are influenced completely by the eddy structure in which they are embedded. However this structure may be changing constantly so that the variety of patterns is almost infinite.

As is the practice with calculations of this nature, the dilution or exposure is calculated for a specific meteorological condition. However, meteorological conditions are characterized by change so that the probability of encountering protracted periods of a specific meteorological condition is rather low, especially in the lower atmosphere. Thus the "steady state" estimates made for large travel times may become increasingly unrealistic. The mean wind speeds given in Table 2 (page 17) are averaged over the space governed by the radiosonde flight column to 35,000 ft from a given station. In the aircraft flight problem not only the winds in the area of flight but the winds in the area affected by the contaminants should be characterized in terms of space and time variability. Such a climatic summary for the specific areas is required to adequately appraise the environmental problem. Then one can assess the probability of certain levels of environmental effects based on the climatic summaries. Wind velocity shear in the vertical is an important factor in dispersing materials in the atmosphere, particularly over long travel times. In the lower 5000 ft of the atmosphere the average veering is 20° to 90°. To a first approximation, one may assume that this veering is evenly distributed throughout the layer.

Another factor not specifically included in the model is the effect of large-scale vertical motions in the atmosphere. However it is felt that the effect of this factor is sufficiently allowed for by the range of C_z appearing in Table 2.

Altitudes as boundaries for certain physical processes in the atmosphere are not intended to be rigidly defined. In deriving the values of parameters and altitudes of applicability, some space and time

average thought to be reasonable was used to provide an internally consistent model. In some cases, only an educated guess was available. Particularly difficult or impossible to incorporate in a general model is the effect of changes of thermal stability with altitude. Vertical temperature soundings commonly show layers of stable and unstable air at various altitudes. Vertical diffusion of contaminants released between stable layers may be limited almost as if bound by horizontal barriers above and below. An analysis of temperature soundings in the region of interest would indicate the severity of such a problem. In coastal regions a land and sea breeze may have to be accounted for in the analysis. The vertical extent of sea breezes is normally about 3000 ft, the land breeze about 1500 ft, and the overall land-sea breeze system in the vertical extends to about 10,000 ft.

Noteworthy among the meteorological situations not adequately covered by a general model is one such as the capping inversion in the Los Angeles area. Dispersion of pollutants released in the layer beneath the inversion is largely confined to this layer, while horizontal dispersion is largely confined to the areal extent of the land-sea breeze system. A climatic analysis of the region would indicate the frequency of such adverse meteorological conditions.

Another example of such a region is found near the trade-wind belt in tropical latitudes (roughly 5°N to 25°N in the Northern Hemisphere). These so-called trade-wind inversions are particularly persistent over ocean surfaces or small islands.

If, on the other hand, releases are consistently made well above the capping inversion in regions such as these, it is to be expected that exposure levels at the ground would be reduced from those estimated using the models.

Another type of meteorological situation somewhat similar to that just discussed from the point of view of estimating exposure levels at the ground is the so-called polar outbreak. In this case a mass of cold air traveling behind a cold front is normally capped by a strong inversion. Once again, releases beneath the cap of the polar air mass

would increase the hazard problem at the surface for relatively large areas since a strong polar outbreak characteristically moves over hundreds of miles without significant change.

It should also be noted that the model does not account for changes in the stability of the air in the lowest 5000 ft of the atmosphere as the air travels from land to water or vice versa.

The atmospheric diffusion of the fission products that come in contact with the ground, vegetation, buildings, etc., is complicated by the loss due to deposition, which tends to deplete the layer of the plume in contact with the ground, leaving an additional radioactive exposure from the materials so deposited. The key parameter in the deposition problem is the deposition coefficient for which reliable values must come from experimental measurements. Even so, the deposition phenomenon is believed to be so complicated by interactions among diffusion parameters, surface characteristics, contaminant interactions, carrier-host problems, retention efficiencies, and chemical nature of contaminants and surfaces that interpretation of results is very difficult.

Cloud-droplet scavenging and raindrop scavenging are simplified in the model. It has proved suitable in meteorological practice to characterize a rainfall by rainfall intensity and the average diameter of drops and their terminal velocities (Best[4]). The computed values correspond only approximately to the actual conditions, as the size of the drops always shows a spectral distribution. The curve of Best contains mean values which, in single cases, show remarkable differences, with the extreme range in rainfall rate for a given mean drop size about a factor of two.

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